What have we learned from diffractive hard scattering?

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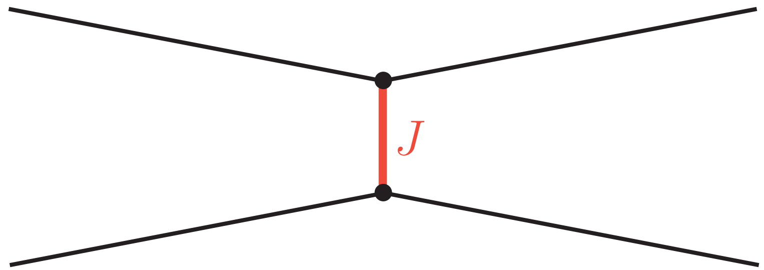
The classic pomeron

(Simplified version)

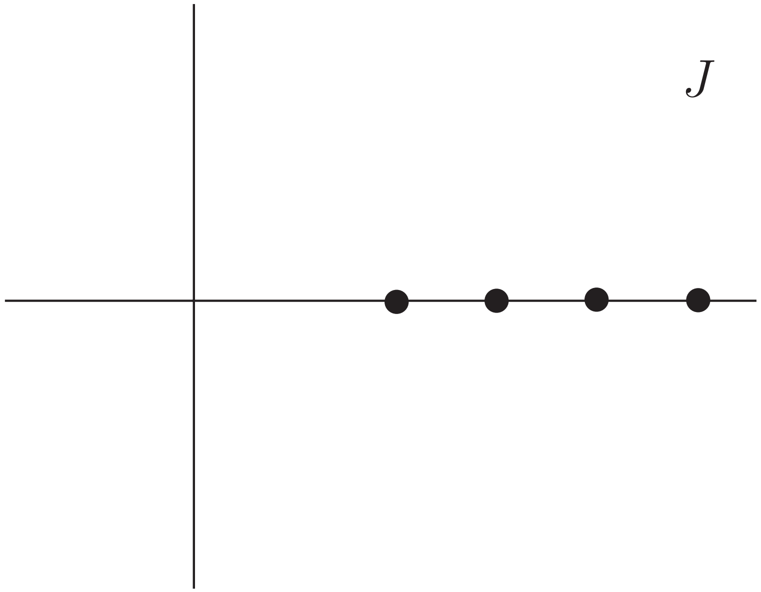
Examine the hadron-hadron scattering amplitude A for large s, fixed t.

Write the amplitude as a sum of exchanges of certain particles of spin J,



The sum

$$A \approx \sum_{J=2}^{\infty} \frac{\beta(J)(-1)^J (s/s_0)^J}{t - m^2(J)}$$

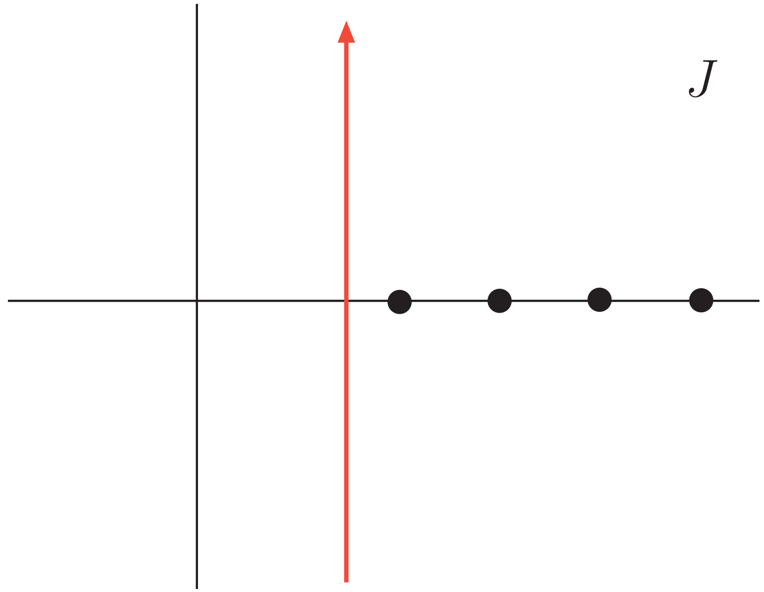


Here s^J comes from

$$p_A^{\mu_1} \cdots p_A^{\mu_J}\ p_B^{\nu_1} \cdots p_B^{\nu_J}\ (g_{\mu_1\nu_1} \cdots g_{\mu_J\nu_J} + \cdots).$$

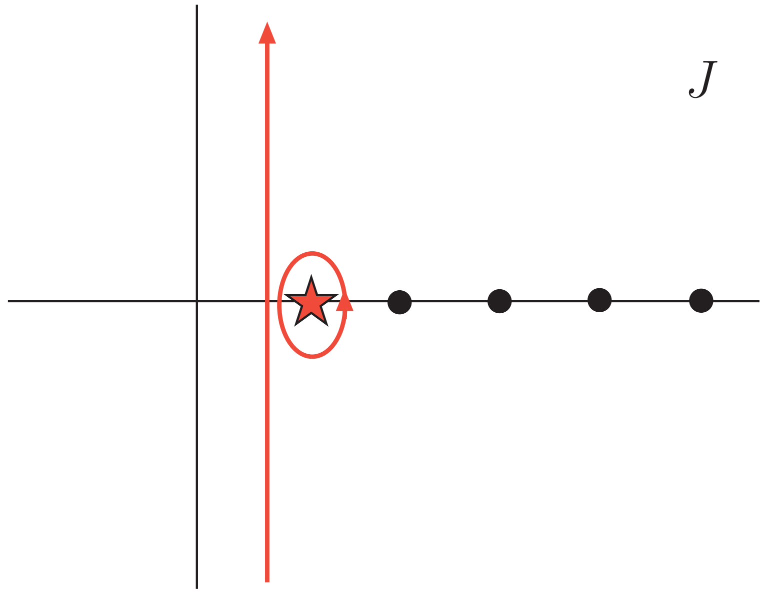
The terms with higher J grow faster with s.

Write the sum as an integral over a contour just to the left of the first particle J.



$$A \approx \frac{-1}{2\pi i} \int_{c-i\infty}^{c+i\infty} dJ \; \frac{\pi}{\sin(\pi J)} \; \frac{\beta(J)(s/s_0)^J}{t - m^2(J)}.$$

Move the contour to the left. The contribution from the rightmost pole dominates for $s \to \infty$.



The pole comes from the zero of

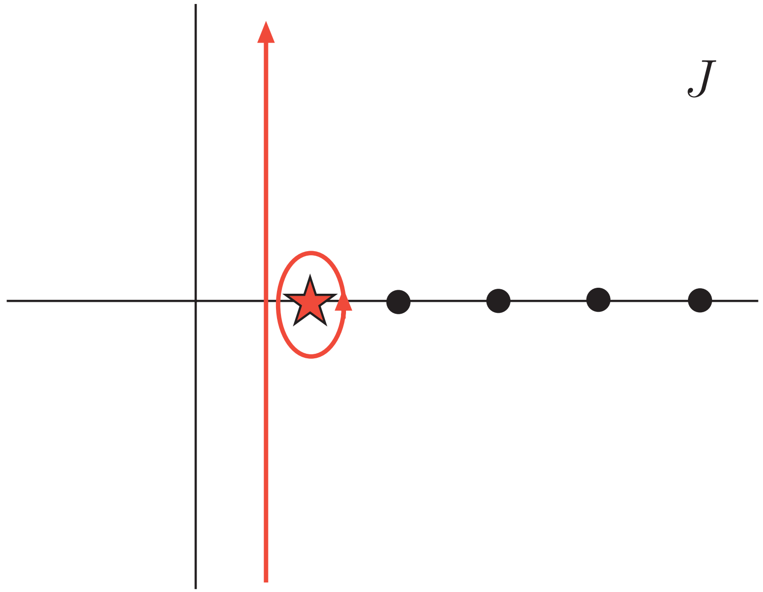
$$t - m^2(J)$$

at

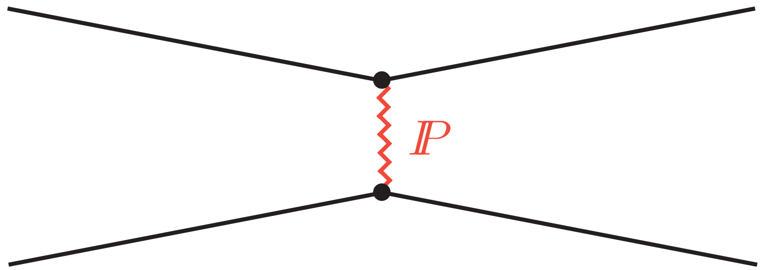
$$J = \alpha(t)$$

This gives

$$A \approx \frac{\pi\alpha'(t)}{\sin(\pi\alpha(t))}\,\beta(\alpha(t))\;(s/s_0)^{\alpha(t)}$$



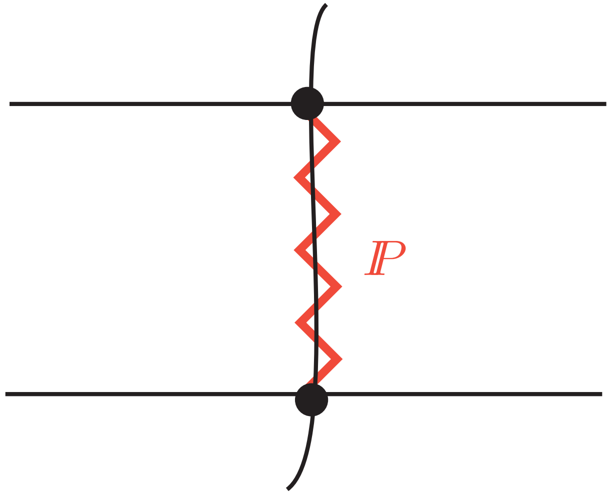
The leading pole, the "pomeron" is at $\alpha(t) \approx 1.08$ with a weak t dependence.



Some important variations

Total cross section,
$A + B \to X$.

$$\sigma_T \propto (s/s_0)^{\alpha(0)-1}$$

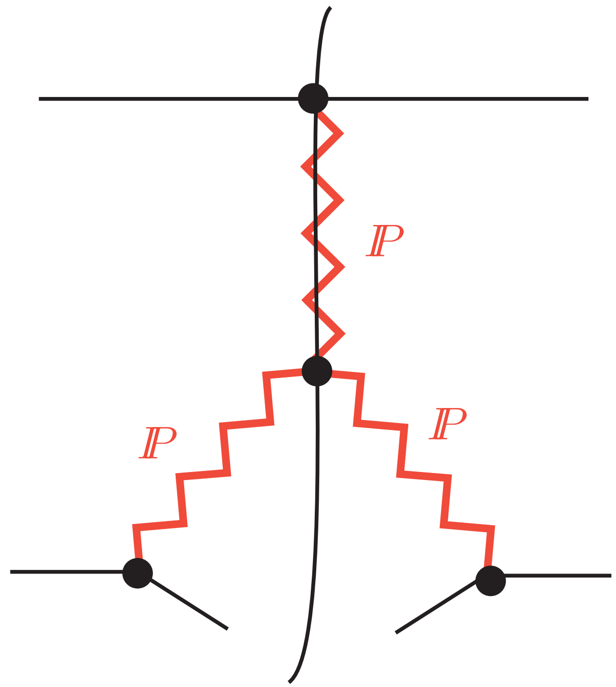


Then the total cross section slowly grows with s.

Single diffractive scattering,
$A + B \to A' + X$. Define

$$t = (P'_A - P_A)^2$$

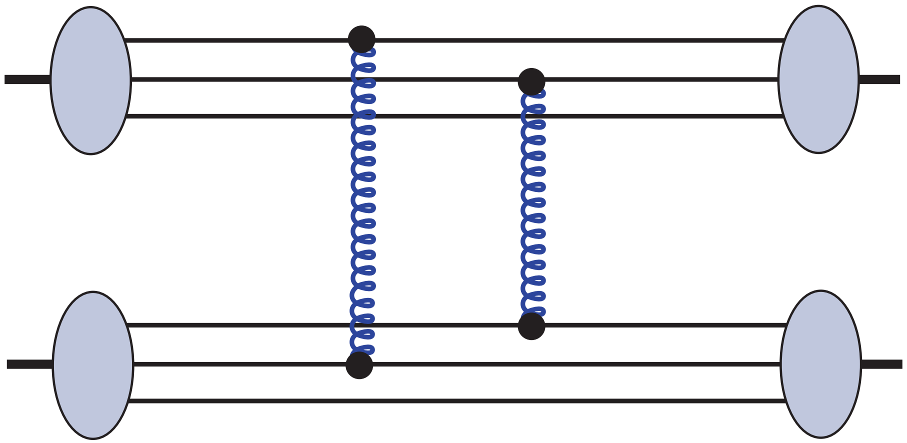
$$x_{\mathbb{P}} = (P'_A - P_A) \cdot P_B / P_A \cdot P_B$$



Then

$$\frac{d\sigma}{dx_{\mathbb{P}}dt} \propto \left(\frac{1}{x_{\mathbb{P}}}\right)^{2\alpha(t)-1} \times (x_{\mathbb{P}} s/s_0)^{\alpha(0)-1}.$$

Really simple model in QCD

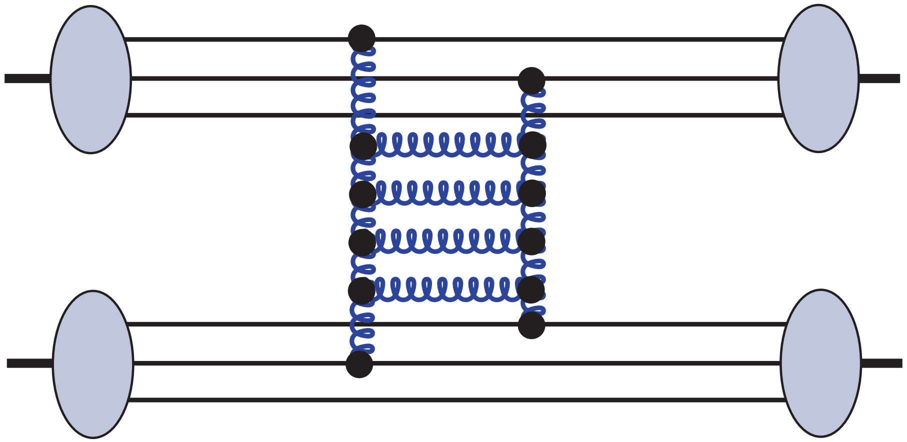


This can't be right because α_s is not small.

But it gives $A \propto (s/s_0)^1$ – not far off.

And it exhibits "color transparency" so a small meson has a small cross section to scatter off of a proton.

Not so simple model in QCD



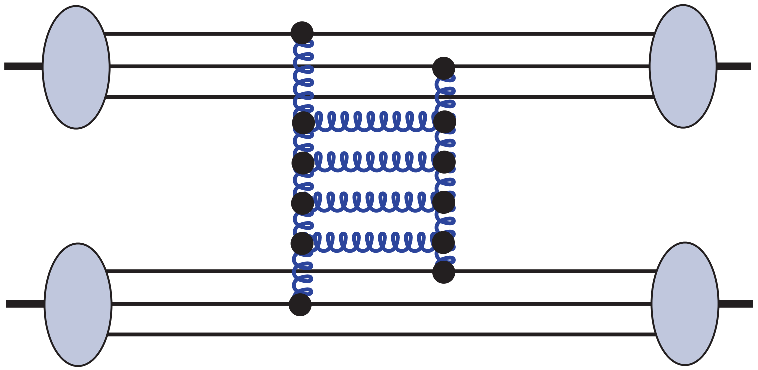
This is the basis of the BFKL pomeron.

It gives $A \propto (s/s_0)^{\alpha(t)}$ with $\alpha(0) \sim 1.4$ to lowest approximation.

The theory is pretty tricky.

The qualitative conclusion

Pomeron exchange is due to exchanged gluons.



Is this testable?

• Yes. Gluons are pointlike. Do an analogue of the Rutherford experiment "from a pomeron."

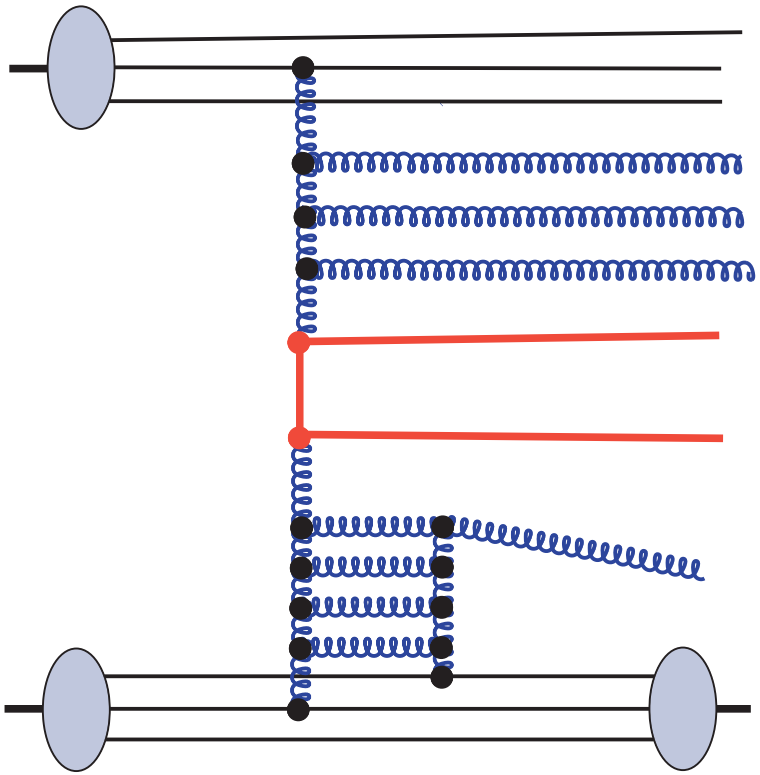
• That is, look for a hard scattering associated with large s small t scattering.

The first experiment

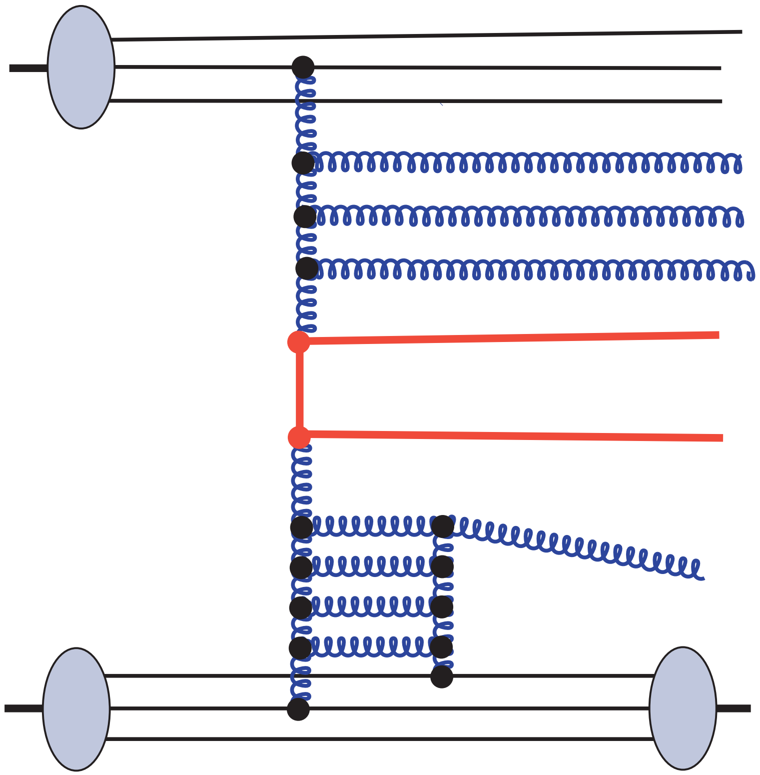
Ingelman and Schlein (1985) proposed to look for

$$p + \bar{p} \to p' + \text{jets} + X.$$

They proposed a model in which the pomeron exchanged in $p \to p'$ was like a hadron that could have a parton distribution.

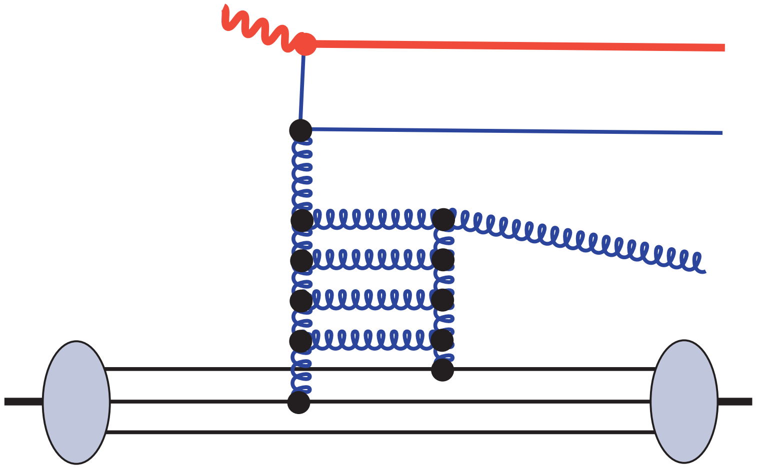


- The UA8 collaboration carried this out and found a non-zero cross section for this.
- Conclusion: The exchanged pomeron couples to pointlike constituents.

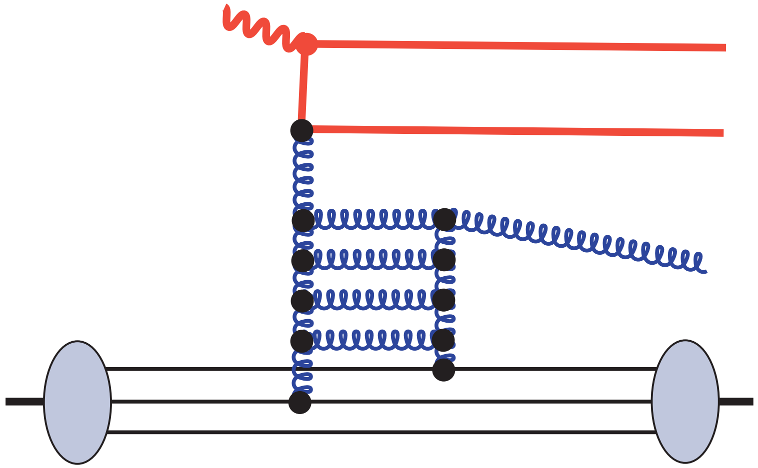


Try diffractive DIS.

The proton is scattered with small t and a small fractional energy loss $x_{\mathbb{P}}$.



Does the pomeron couple to pointlike quarks?



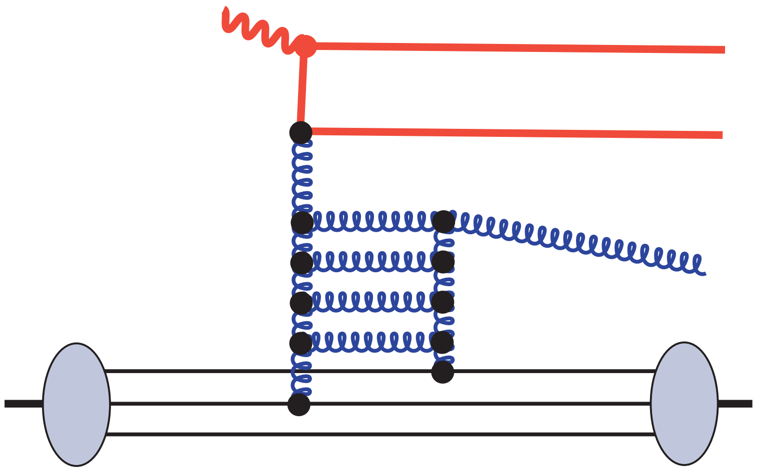
Does the pomeron couple to pointlike gluons?

Theoretical formulas for DIS

$$\frac{dF_2^{\text{diff}}(x, Q^2; x_{I\!P}, t)}{dx_{I\!P}\, dt} = \sum_a \int d\xi \, \frac{df_{a/A}^{\text{diff}}(\xi, \mu^2; x_{I\!P}, t)}{dx_{I\!P}\, dt} \hat{F}_{2,a}(x/\xi, Q^2, \mu^2)$$

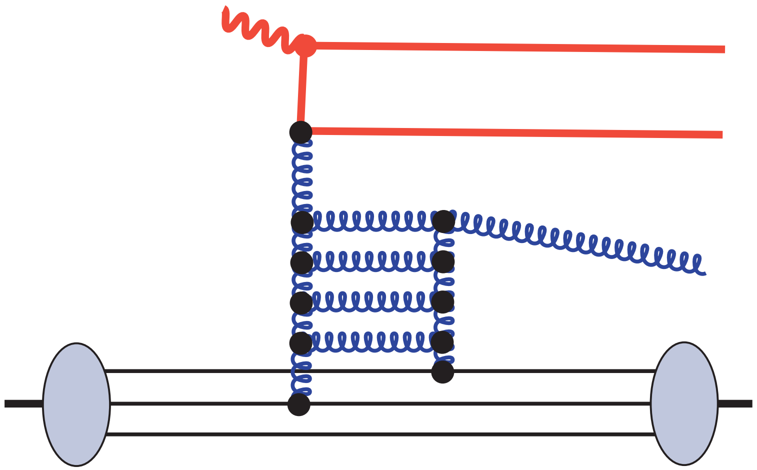
$$t = (P'_A - P_A)^2$$

$$x_{I\!P} = (P'_A - P_A) \cdot Q / P_A \cdot Q$$



$$\frac{dF_2^{\rm diff}(x,Q^2;x_{I\!P},t)}{dx_{I\!P}\,dt} = \sum_a \int d\xi\ \frac{df_{a/A}^{\rm diff}(\xi,\mu^2;x_{I\!P},t)}{dx_{I\!P}\,dt}\hat{F}_{2,a}(x/\xi,Q^2,\mu^2)$$

- a is parton type (gluon in picture).
- ξ is parton momentum fraction $\equiv \beta x_{I\!P}$.
- $\hat{F}_{2,a}$ is calculated partonic structure function.

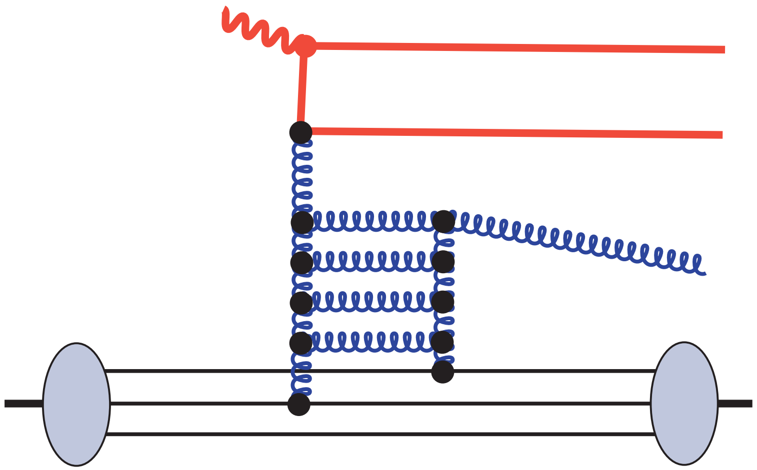


- $df_{a/A}^{\rm diff}/dx_{I\!P}\,dt$ is a "diffractive parton distribution function."

- That is, the probability to find the parton while the proton is diffractively scattered.

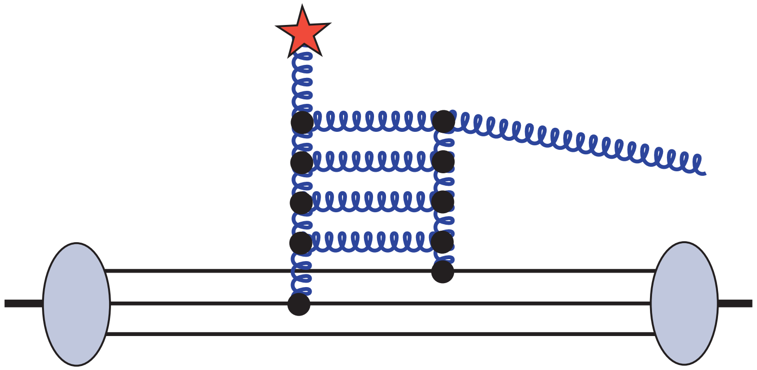
$$\frac{dF_2^{\text{diff}}(x, Q^2; x_{I\!P}, t)}{dx_{I\!P}\, dt} = \sum_a \int d\xi \; \frac{df_{a/A}^{\text{diff}}(\xi, \mu^2; x_{I\!P}, t)}{dx_{I\!P}\, dt} \hat{F}_{2,a}(x/\xi, Q^2, \mu^2)$$

- This factorization formula is a (testable) prediction of QCD.
- See proof by John Collins.
- $df_{a/A}^{\text{diff}}/dx_{I\!P}\, dt$ obeys the ordinary evolution equation.



QCD motivated expectations

- $df_{a/A}^{\text{diff}}/dx_{I\!P}\,dt$ is not zero.
- $df_{a/A}^{\text{diff}}/dx_{I\!P}\,dt$ is biggest for $a =$ gluon.



$$\frac{df_{a/A}^{\text{diff}}(\xi,\mu^2;x_{I\!P},t)}{dx_{I\!P}\,dt} = \frac{1}{8\pi^2}\,|\beta_A(t)|^2\,x_{I\!P}^{-2\alpha(t)}\,f_{a/I\!P}(\xi/x_{I\!P},t,\mu^2)$$

Experimental results for diffractive DIS

- The cross section is not zero. Yes.

- The QCD factorization formula works.

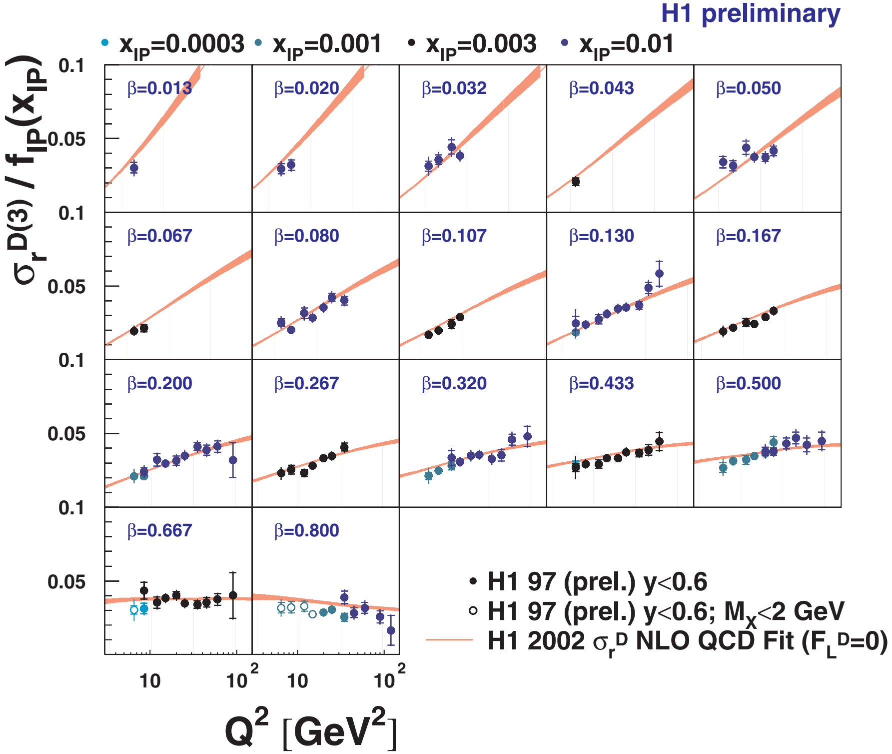
  Yes, consistent results are obtained between diffractive DIS and diffractive DIS with jet production. (H1 results, not shown)

- The $x_{\mathbb{P}}^{-2\alpha(t)}$ factor is there. Yes. (But maybe $\alpha(t)$ is too big.)

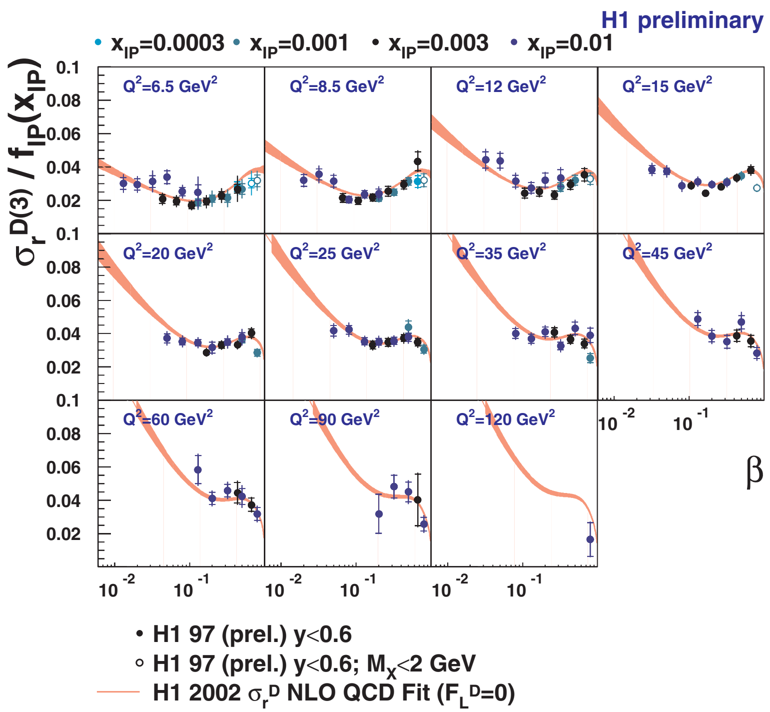
- $df_{a/A}^{\text{diff}}/dx_{\mathbb{P}}\,dt$ is biggest for $a =$ gluon. Yes

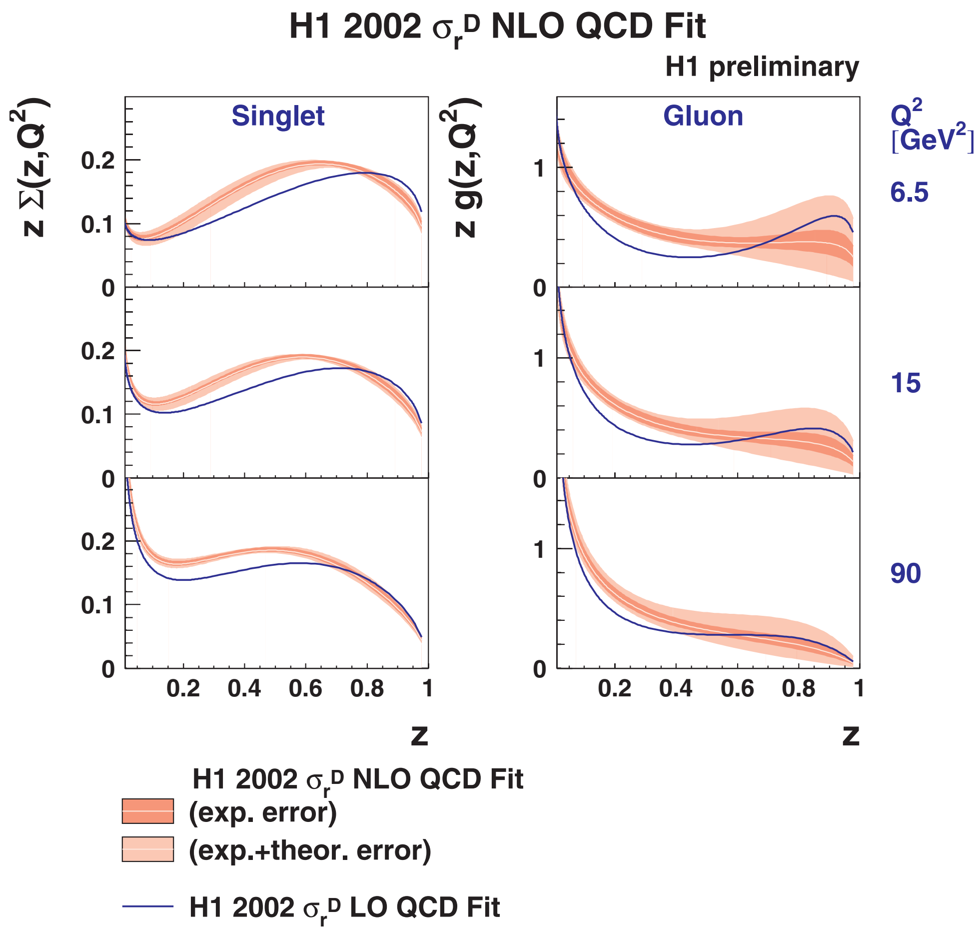
- See H1 fits from F. P. Schilling, ICHEP 2002, following.

Q^2 dependence of data and fit. Note how flat it is at large β.



β dependence of data and fit. Note how slowly it falls at large β.

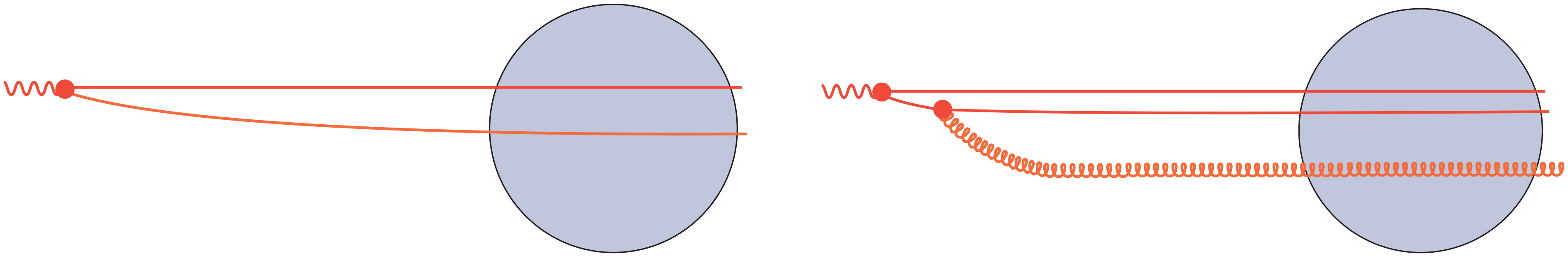




Quark distribution is quite flat

Gluon distribution dominates

View from the proton rest frame



The hard interaction is a long distance $\sim m/x_{\mathbb{P}}$ from the proton.

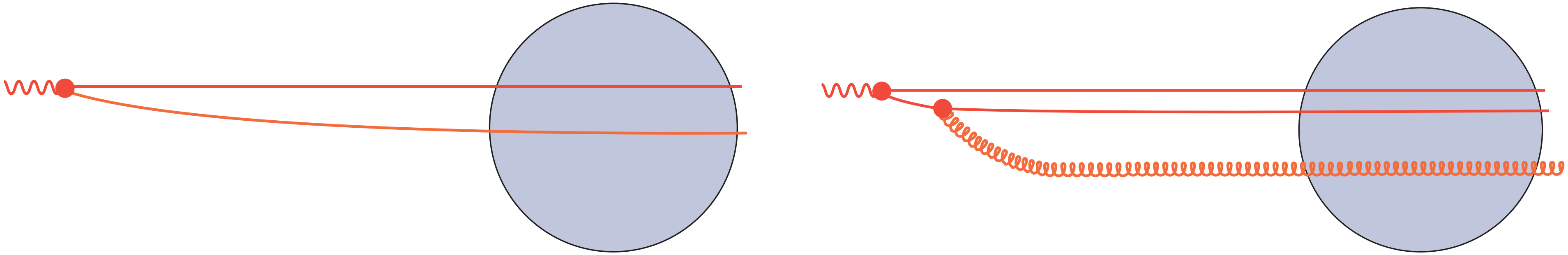
This is just another way of looking at the factorized formula.

$$\frac{dF_2^{\mathrm{diff}}(x,Q^2;x_{\mathbb{P}},t)}{dx_{\mathbb{P}}\,dt} = \sum_a \int d\xi\ \frac{df_{a/A}^{\mathrm{diff}}(\xi,\mu^2;x_{\mathbb{P}},t)}{dx_{\mathbb{P}}\,dt} \hat{F}_{2,a}(x/\xi,Q^2,\mu^2)$$

In this frame, instead of getting a from the proton, we produce $\bar{a}$ that later hits the proton. ($a = q$ on left, $a = g$ on right.)

A model that works pretty well

[Hautmann, Kunszt, DES]



The partons can get through the proton without destroying it if their transverse separation is pretty small.

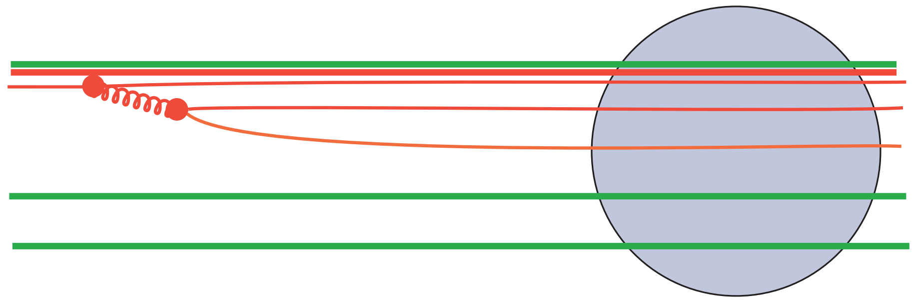
This is because the proton is transparent to color singlet objects in QCD.

This is a surprizing view of diffraction. The proton doesn't miss the obstacle, it goes through it, or rather the obstacle goes through the proton.

Hadron-hadron collisions

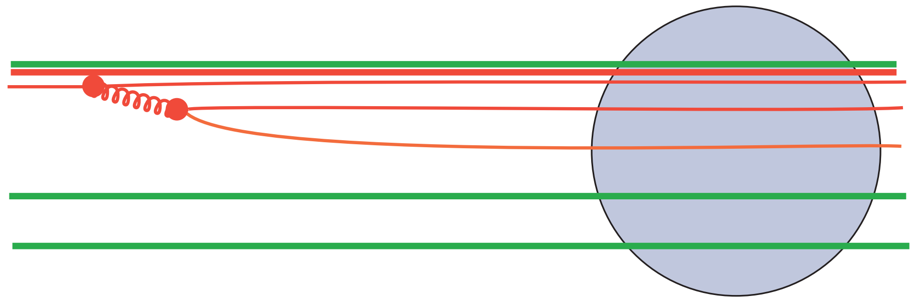
Consider $p+\bar{p}\to p'+\text{jets}+X$

Look in the rest frame of the diffracted proton.



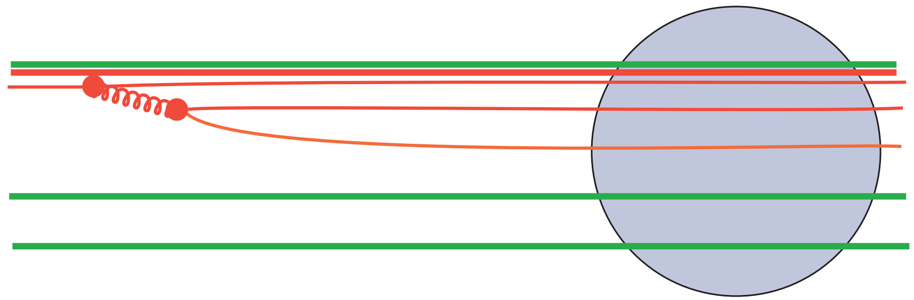
Here the hard process is $q+\bar{q}\to q+\bar{q}$ via gluon exchange.

The high p_T q and $\bar{q}$ have transverse separation $1/p_T$.



At the top, I added a fast color 3 line (red) and a fast color $\bar{3}$ line (green) at the transverse position of the original antiquark.

There are two additional fast color $\bar{3}$ lines representing incoming spectator antiquarks.



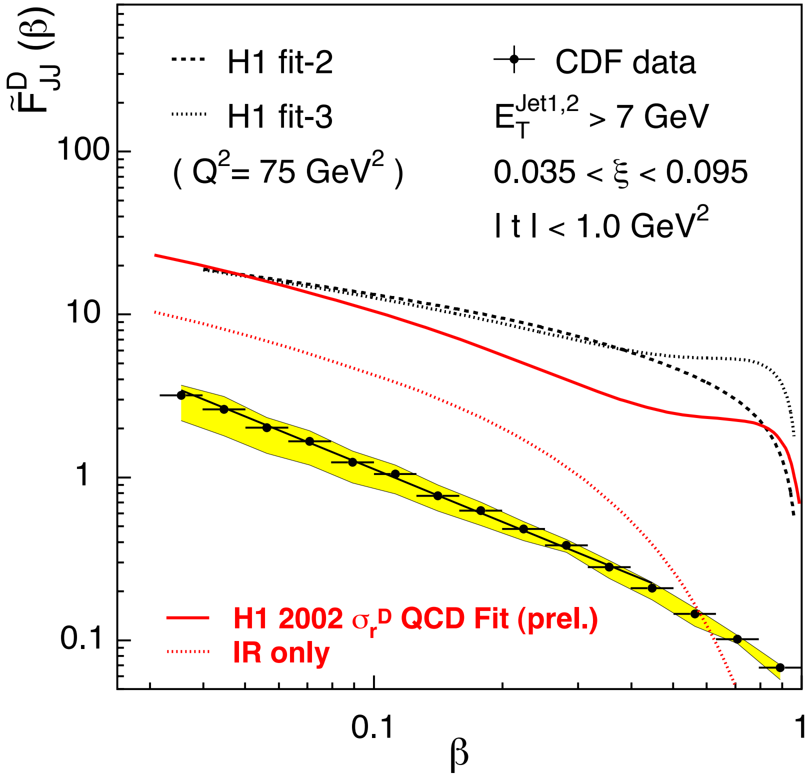
If we could forget about the green lines, we would have

$$\frac{\sigma^{\rm diff}_{\rm jets}(x_{I\!\!P},t)}{dx_{I\!\!P}\,dt} = \sum_{a,b}\int d\xi_a \int d\xi_b\ \frac{df^{\rm diff}_{a/A}(\xi_a;x_{I\!\!P},t)}{dx_{I\!\!P}\,dt}\ f_{b/B}(\xi_b)\,\hat\sigma^{\rm jets}_{ab}$$

But we can't forget about the green lines. Thus QCD predicts that this formula should *not* work.

Test that diffractive factorization does not work

Diffractive dijets at the TEVATRON:

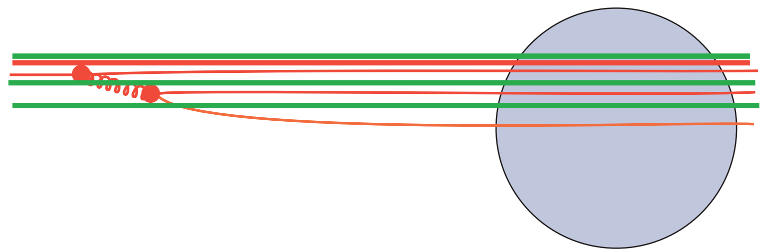


(Graph from J. P. Schilling, ICHEP 2002)

How does it happen, then?

Here are two possibilities for what dominates in $p + \bar{p} \to p' +$ jets $+ X$.

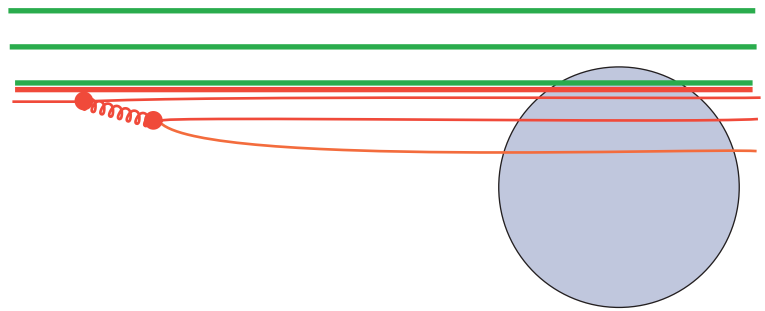
Maybe the incoming $\bar{p}$ is scrunched to a small transverse size.



Then it would be a color singlet that could get through the proton without destroying it.

Prediction: the $\bar{p}$ remnants would have quite large transverse momenta.

Maybe the incoming $\bar{p}$ mostly misses the proton.



Prediction: the $\bar{p}$ remnant region would be rather quiet.

Conclusions

- The Standard Model has some predictions about how diffractive should look if examined with a hard probe.

- The predictions are confirmed experimentally.

- The predictions for diffractive deeply inelastic scattering involve some of QCD's more subtle features.

- More experimental and theoretical work would help us better understand hard diffractive scattering for hadron-hadron collisions.